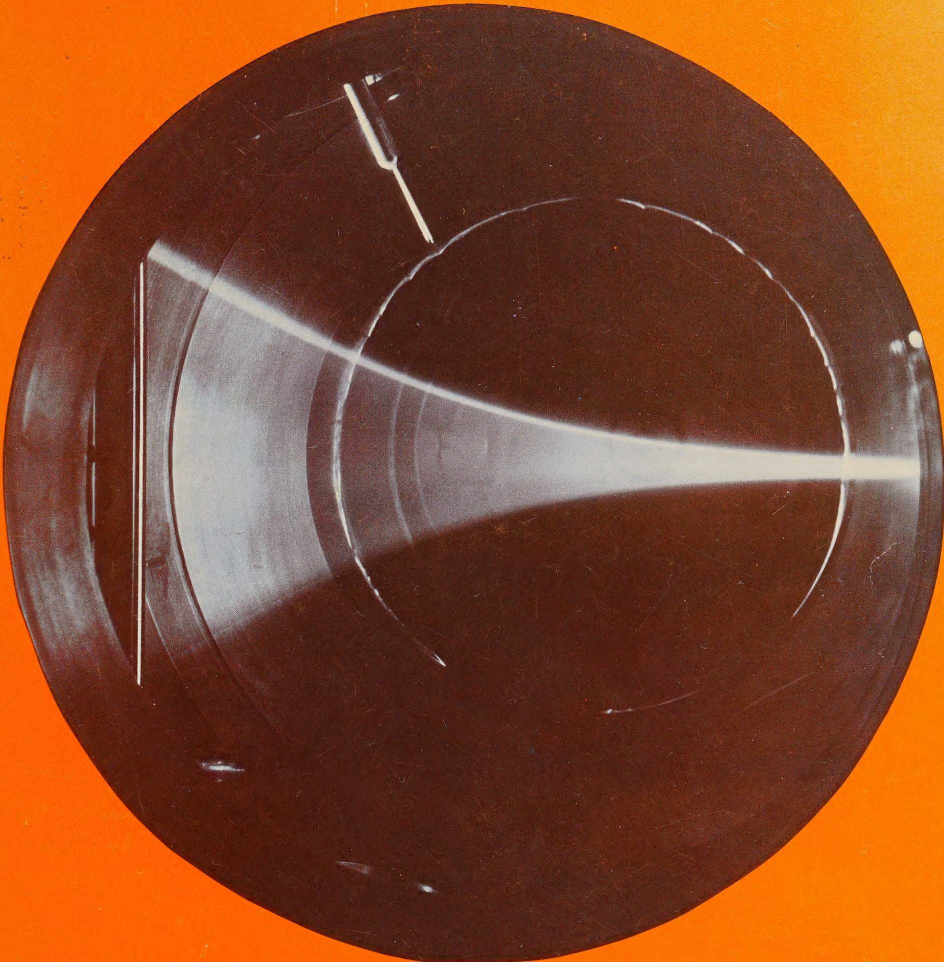
ERDA-76/110/0

Fusion Power by Magnetic Confinement

ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION
USA

Program Plan/
Executive
Summary



Division of Magnetic
Fusion Energy

ABOUT THE COVER:

High temperature hydrogen plasma, the fuel of future fusion reactors, follows invisible magnetic lines of force in this magnetic mirror experiment at the Lawrence Livermore Laboratory.

DISCLAIMER

This Program Plan spells out the options available to the Division of Magnetic Fusion Energy under a range of possible funding assumptions called "Program Logics". As such, it represents a Division document and not necessarily the views of the top ERDA management. The Division believes, however, that the range of program logics and options presented will cover any eventualities which may arise in the course of setting program strategies with ERDA management, OMB, and Congress.

Energy Research and Development Administration

Division of Magnetic Fusion Energy Washington, D.C. 20545

The attainment of economic and safe fusion power has been described as the most sophisticated scientific problem ever attacked by mankind. The fusion research program began in the early 1950's and has progressed through a succession of scientific and financial crises. In recent years there have been a number of experimental achievements whose cumulative impact has been to give confidence that the ultimate goal—demonstration of practical fusion power—can very likely be achieved by the late 1990's.

The four volume Fusion Power Research and Development Program Plan treats the technical, schedule and budget projections for the development of fusion power using magnetic confinement. It was prepared on the basis of current technical status and program perspective. A broad overview of the probable facilities requirements and optional possible technical paths to a demonstration reactor is presented, as well as a more detailed plan for the R&D program for the next five years. The "plan" is not a roadmap to be followed blindly to the end goal. Rather it is a tool of management, a dynamic and living document which will change and evolve as scientific, engineering/technology and commercial/economic/environmental analysis and progress proceeds. The use of plans such as this one in technically complex development programs requires judgment and flexibility as new insights into the nature of the task evolve.

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GOALS, OBJECTIVES, AND APPLICATIONS

- The presently-established program goal of the fusion program is to DEVELOP AND DEMONSTRATE PURE FUSION CENTRAL ELECTRIC POWER STATIONS FOR COMMERCIAL APPLICATIONS.
- Short term objectives of the program center around establishing the technical feasibility of the more promising concepts which could best lead to commercial power systems.
- There exist potential applications of fusion systems other than central station electric plants. These include:
    - Direct production of hydrogen gas and/or synthetic fuels
    - Direct energy production for chemical processing
    - Fissile fuel production
    - Fission product waste disposal
    - Fusion-fission hybrid reactors.

Actual commercialization of fusion reactors is assumed to occur primarily through a developing fusion vendor industry working with Government and the electric utilities.

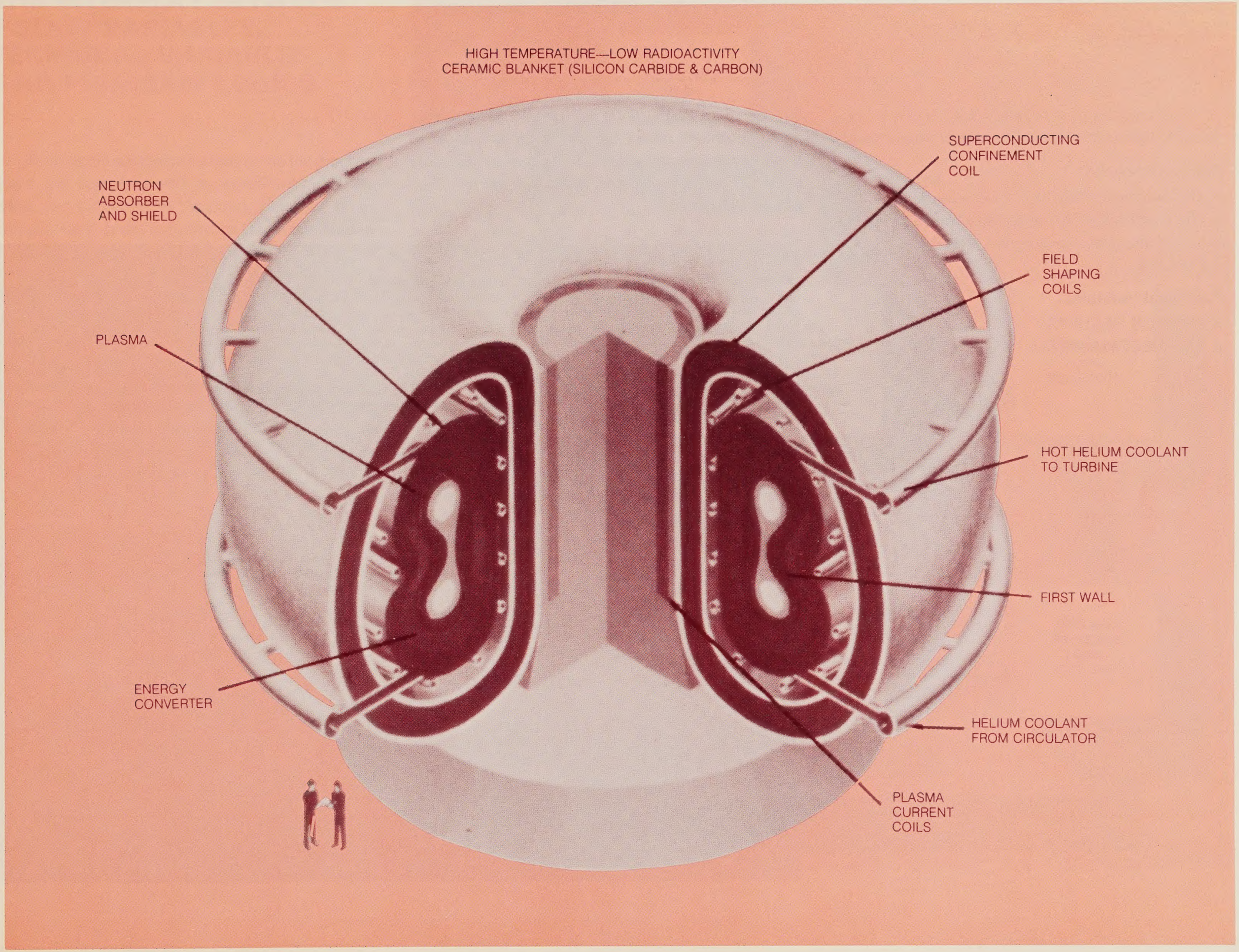
Key to success in this effort is a cooperative effort in the R&D phase between national laboratories and industry.

FUSION ADVANTAGES

- An effectively inexhaustible supply of fuel—at essentially zero cost on an energy production scale;
- A fuel supply that is available from the oceans to all countries and therefore cannot be interrupted by other nations;
- Inherent safety with no possibility of nuclear runaway;
- No chemical combustion products;
- No afterheat cooling problem in case of an accidental loss of coolant;
- No use of weapons grade materials; hence no possibility of diversion for clandestine purposes;
- Low amount of radioactive by-products with significantly shorter half-life relative to fission reactors.

FUSION REACTOR CONCEPT

One type of fusion reactor concept is based on confinement of a plasma with a noncircular "kidney-shaped" cross-section. Preliminary indications are that plasmas can be contained in the non-circular configuration with magnetic fields much lower in strength than those required in standard tokamaks. Such a configuration could therefore substantially reduce the cost of tokamak reactors because lower cost, lower strength magnetic fields could be used.


HIGH TEMPERATURE—LOW RADIOACTIVITY
CERAMIC BLANKET (SILICON CARBIDE & CARBON)
NEUTRON ABSORBER AND SHIELD
PLASMA
ENERGY CONVERTER
SUPERCONDUCTING CONFINEMENT COIL
FIELD SHAPING COILS
HOT HELIUM COOLANT TO TURBINE
FIRST WALL
HELIUM COOLANT FROM CIRCULATOR
PLASMA CURRENT COILS

POLICY AND TECHNICAL VARIABLES

The most significant policy and technical variables that affect the pace of the fusion program are:

Policy Variables:

- The perceived NEED for fusion power
- The nation's INTENT (what is expected by when? What priority does the program have?)
- FUNDING

Technical Variables:

- PHYSICS RESULTS
- ENGINEERING RESULTS

PROGRAM LOGICS

Because NEED, INTENT, and FUNDING are finally decided by others, the fusion program requires a number of plans by which the program can be conducted. The following plans, referred to as LOGICS, are considered.

LOGIC I. LEVEL OF EFFORT RESEARCH
Research and development are supported at an arbitrary level in order to develop basic understanding. (If this pace were continued, a practical fusion power system might never be built).

LOGIC II. MODERATELY EXPANDING, SEQUENTIAL
Funds are expanding but technical progress is limited by the availability of funds. Established commitments are given funding priority but new projects are not started until funds are available. In spite of limited funding a number of problems are addressed concurrently. (At this rate, a fusion demonstration reactor might operate in the early 21st century.)

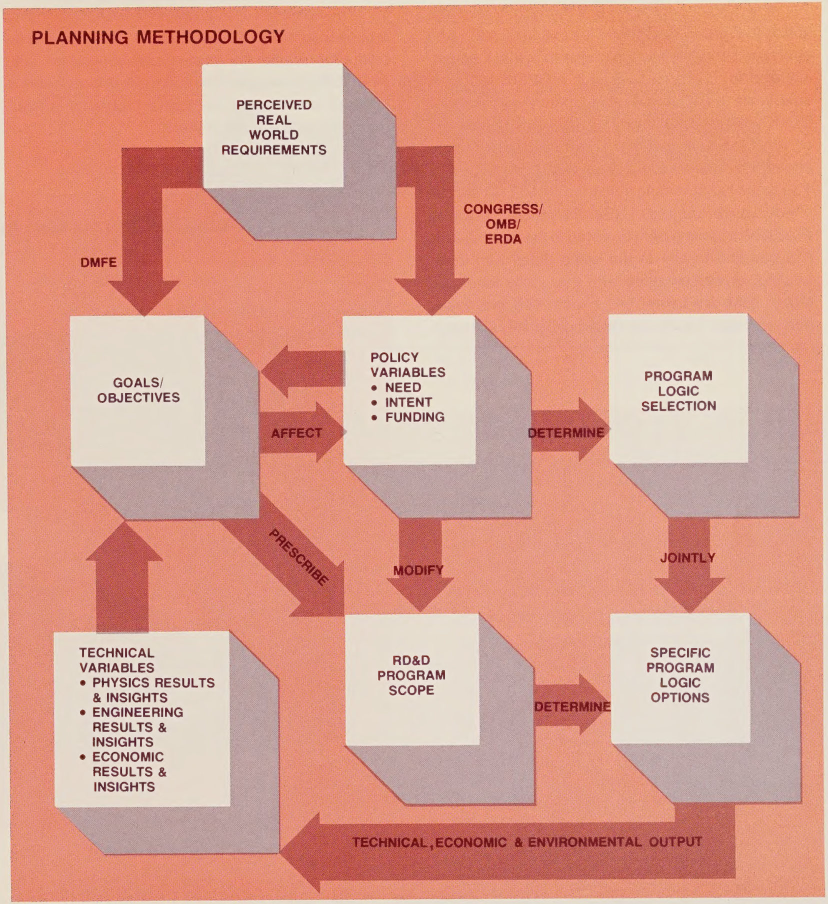
LOGIC III. AGGRESSIVE
The levels of effort in physics and engineering are expanded according to programmatic need, assuming that adequate progress is evident. New projects are undertaken when they are scientifically justified. Many problems are addressed concurrently. Funding is ample but reasonably limited. (This program would be aimed at an operating demonstration reactor in the late 1990's.)

LOGIC IV. ACCELERATED
A great many problems are addressed in parallel and new projects are started when their need is defined. Fabrication and construction is carried out on a normal basis with enough priority to minimize undue delays. The availability of funds is still limited but a secondary factor in program planning and implementation. (This approach would be aimed at demonstration reactor operation in the early to mid-1990's.)

LOGIC V. MAXIMUM EFFECTIVE EFFORT
Manpower, facilities and funds are made available on a priority basis; all reasonable requests are honored immediately. Fabrication and construction is expedited on a priority basis so that completion times for major facilities are reduced to a practical minimum. (An operating demonstration plant around 1990 would be the program goal.)

THE INTERPLAY BETWEEN POLICY VARIABLES, TECHNICAL VARIABLES AND PROGRAM LOGICS

Real world requirements determine the program goals and objectives and, as perceived by ERDA, OMB, and Congress, fix the policy variables. An interaction takes place between the Division of Magnetic Fusion Energy and ERDA, OMB and Congress, and eventually ERDA, OMB and the Congress determine which LOGIC the program is to be on. The goals and objectives as modified by the policy variables prescribe the R&D program scope. The choice of LOGIC influences the activity within the program scope and a specific path (called a Logic Option) emerges. The results from following that option constitute the technical variables which the Division evaluates in the process of proposing the program goals and adjusting objectives.

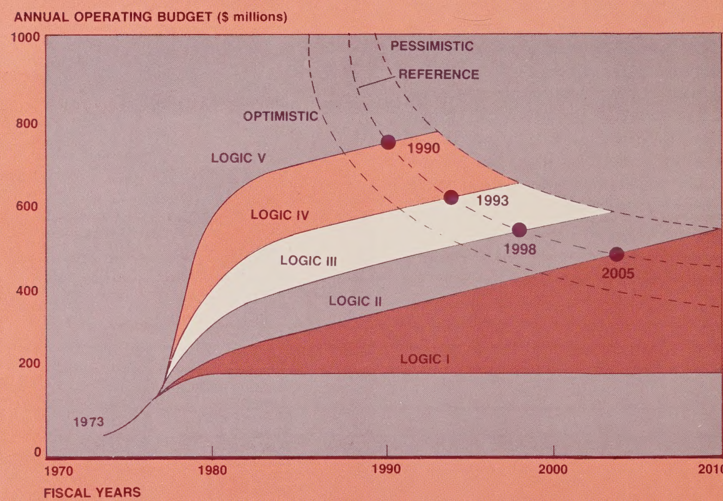


The Logics, numbered I through V are differentiated grossly according to funding levels* of the operations budget. The funding is such that the funding level for Logic I will result in a DEMO far out in time, while the funding level for Logic V will result in a DEMO as soon as is practically possible. The degree of "pessimism" or "optimism" assumed substantially affects the projected date for operation of the DEMO. The projected operating date for a DEMO will also be affected by the degree of "risk" the program is willing to accept in moving from one step to the next. Clearly it is possible to aim at the same dates with lower funding, or earlier dates with the same funding if higher risks are taken, i.e., if less R&D and fewer demonstrated results are required to justify succeeding steps.

All costs are in constant FY 1978 dollars.

The tokamak is currently the most promising approach to fusion, and is closer to achieving a demonstration reactor for commercial application than other fusion concepts. The major effort, world-wide is devoted to tokamaks, but active programs in alternate concepts are maintained.

FUSION R&D PROGRAM OPERATING BUDGET FOR LOGIC I THRU V



LOGIC III

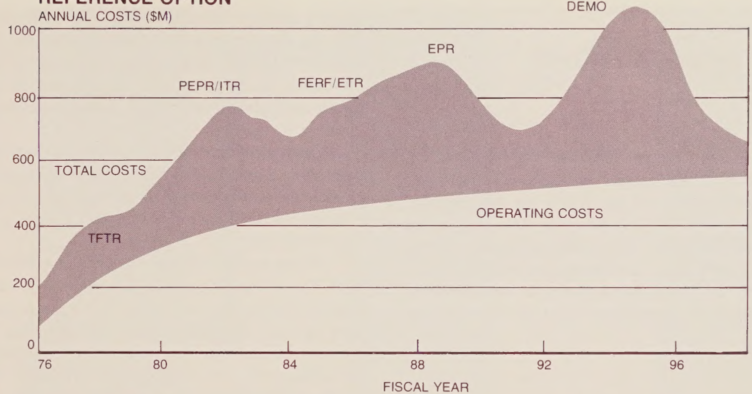
A Logic III Reference Option has been considered in detail.

The major facilities shown are the following:

- Demonstration Reactor (DEMO)
- Experimental Power Reactor (EPR)
- Prototype Experimental Power Reactor or Ignition Test Reactor (PEPR/ITR)
- Tokamak Fusion Test Reactor (TFTR)
- Doublet III (D-III)
- Poloidal Divertor Experiment (PDX)
- Princeton Large Torus (PLT)
- Fusion Engineering Research Facility or Engineering Test Reactor (FERF/ETR)
- Large Mirror Experiment (MX)
- Baseball Mirror Device (BB)
- 2X Mirror Device (2X)
- Large Staged Scyllac (LSS)
- Staged Scyllac (SS)
- Scyllac

The characteristics of these facilities are described in ERDA-76/110/2

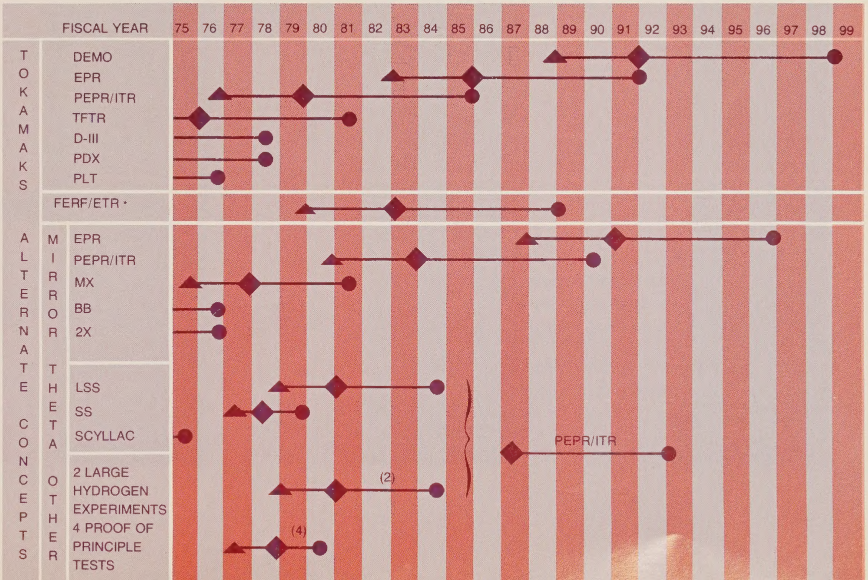
TOTAL PROGRAM ANNUAL COSTS vs. TIME FOR THE LOGIC III REFERENCE OPTION



LOGIC III REFERENCE OPTION

● BEGIN OPERATION
◆ BEGIN TITLE 1 Division Decision Occurs 1 Year Earlier
▲ BEGIN CONCEPTUAL DESIGN

*MAJOR ENGINEERING FACILITY



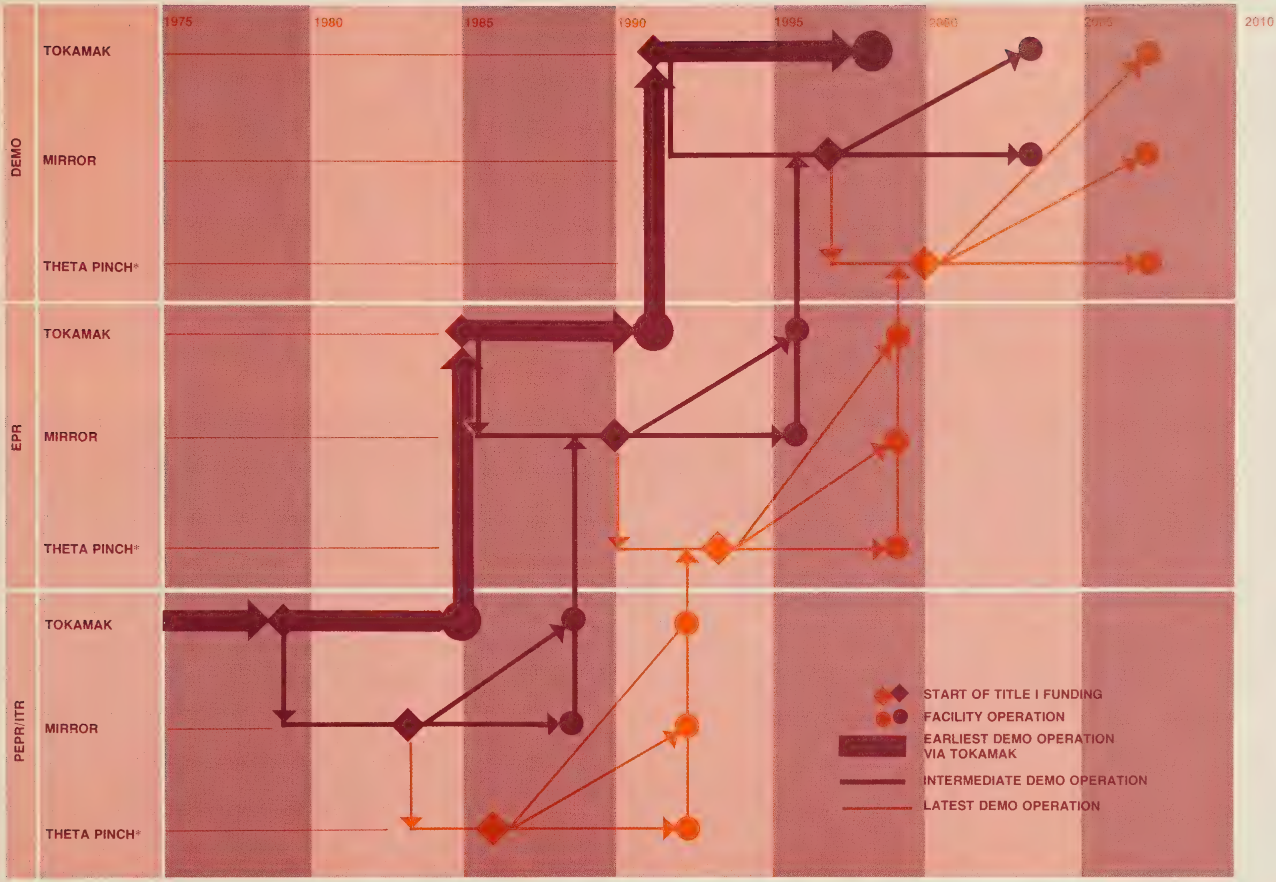
LOGIC III ALTERNATE PATHS

As decision dates occur for major facilities, it is possible that the decision will be to wait for further information. Note on the figure, the first decision along the PEPR/ITR tokamak line. The result of this decision will be to either construct a tokamak PEPR/ITR or delay until more information becomes available for both tokamaks and mirrors. Assuming that the result of the decision is to wait, the next identified decision point is along the mirror PEPR/ITR line. This decision can result in three alternatives: (1) construct a tokamak PEPR/ITR; (2) construct a mirror PEPR/ITR; (3) delay until more information becomes available from other approaches to magnetic fusion.

A decision made for one confinement concept (say tokamak PEPR/ITR) will not prevent a second decision, at a later point in time, for a second confinement method (say mirror or other alternate concept PEPR/ITR).

The figure shows that the earliest possible Fusion Power Demonstration Reactor would be a tokamak operating around 1998. Note that this operation date could be delayed until 2004 (and could be a mirror) if the 1979 decision resulted in a decision to delay selection of the PEPR/ITR until 1983. If the initiation of the PEPR/ITR is delayed until 1986, the DEMO would operate in 2007.

LOGIC III REFERENCE OPTION PROGRAM PATH ALTERNATIVES



*Other alternate concepts would follow the theta pinch path

OPTIONS

In the planning process, assumptions must be made on the range of possible physics and engineering/technology results and the time at which these results will be forthcoming. This gives rise to a multiplicity of potential paths for each approach to fusion power, called "Options". Analysis shows that many of these results lead to decisions to build large devices which are similar in general character, although they may differ in timing and in physics and engineering detail. Consequently the different options are characterized primarily by the nature of the next major facility to which the particular option path leads.

LOGIC III OPTION MATRIX FOR TOKAMAKS

Option
1. Reference
2. Optimistic
3. Pessimistic
4. Reassessment
5.
6.
7.

LOGIC III: OPTION MATRIX FOR MIRROR AND TOROIDAL THETA PINCH

Option
Mirror
1. Reference
2. Optimistic
3. Pessimistic
4. Reassess
5. Fusion/Fission
6. FERF/ETR
Toroidal Theta Pinch
1. Reference
2. Optimistic
3. Pessimistic
4. Reassess

*LARGE STAGED SCYLLAC

Description	Results of Critical Parameter Assessment in 1979		Best Next Step	Initiation/ Completion Date	Best Next Step	Initiation/ Completion Date	Best Next Step	Initiation/ Completion Date
	Physics	Eng./Tech.						
D-shaped	**G**	**F**	**PEPR/ITR**	**79/85**	**EPR**	**85/91**	**DEMO**	**91/98**
			FERF/ETR	**82/88**				
Doublet	**G**	**G**	**EPR-I**	**79/85**	**EPR-II**	**84/90**	**DEMO**	**88/95**
Circular	**F**	**F**	**LHX**	**79/84**				
			PEPR/ITR	**85/91**	**EPR**	**91/97**	**DEMO**	**98/05**
Any	**P**			**Reassess in 1982 based upon further results from upgrades and TFTR**				
High Field	**G**	**G**	**PEPR/ITR**	**79/85**	**EPR**	**85/91**	**DEMO**	**91/98**
High Field	**G**	**F**	**Reassess**					
Doublet	**G**	**F**	**PEPR/ITR**	**79/85**	**EPR**	**85/91**	**DEMO**	**91/98**

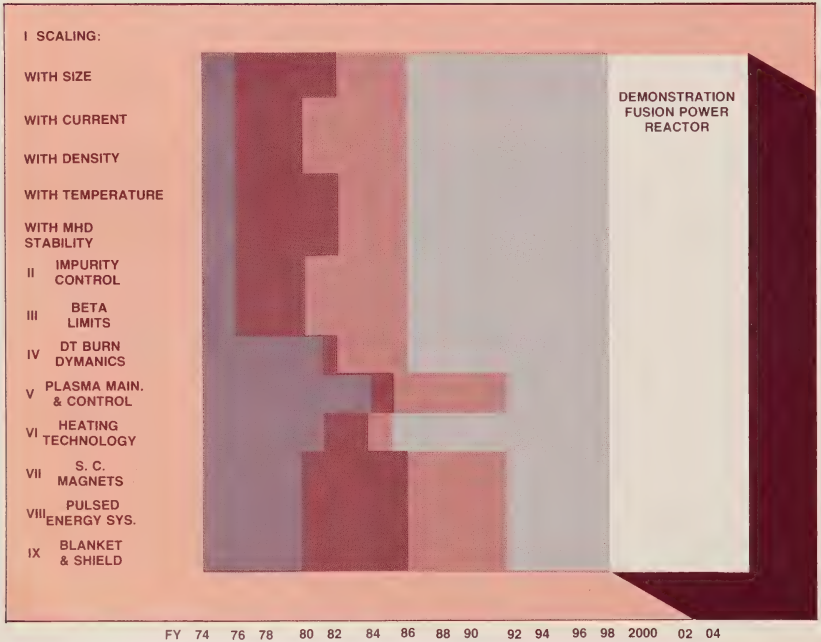
Physics Prototype	I/C	Results of Critical Parameter Assessment—1982		Best Next Step	Initiation/ Completion Date	Best Next Step	I/C	Best Next Step	I/C
		Physics	Eng/Tech.						
MX	77/81	G	F	PEPR	83/89	EPR	90/96	DEMO	97/04
MX	77/81	G	G	PEPR	82/88	EPR	98/94	DEMO	93/01
MX	77/81	F	F	LHX	82/87	EPR	95/01	DEMO	02/09
				PEPR	88/94				
		P	P	—				—	
MX	77/81	F	F	F/F PEPR	83/89	F/F DEMO	90/96		
MX	77/81	F	F	FERF/ETR	82/88	—			
		Assessment—1985							
LSS*	80/84	G	F	PEPR/ITR	86/92	EPR	93/99	DEMO	00/07
LSS*	80/84	G	G	PEPR/ITR	86/89	EPR	90/96	DEMO	97/04
LSS*	80/84	F	F	LHX	85/90	EPR	98/04	DEMO	05/12
				PEPR/ITR	91/97				
LSS*	80/84	P	P						

ROLL-BACK PLANNING

The primary planning approach described thus far may be characterized as "roll-forward", i.e., the current program is considered and, from that consideration, the nature and timing of the next step is determined. A successful fusion power R&D program requires, in addition, a "roll-back" approach in which the nature of the desired end-product, a Fusion Power Demonstration Reactor that extrapolates readily to commercial reactors, is defined in detail and in which the physics and engineering tests required for a DEMO are identified and programs established to provide the required tests. This "roll-back" approach is discussed in Section V of ERDA-76/110/2. Clearly "roll-forward" and "roll-back" approaches must both be used for a successful fusion R&D program.

In order to build a Fusion Power Demonstration Reactor of any type, certain physics understanding must be demonstrated and certain technological subsystems must be developed. These activities may be categorized as "Major Program Elements".

Overall technological and commercial outlook is determined by the interrelated progress of each Element towards meeting the needs of a fusion DEMO. Tests of the critical physics and/or the technology of the Elements may be made individually in small test facilities and/or collectively in larger facilities. These tests can be described as falling into four classes of tests as follows:

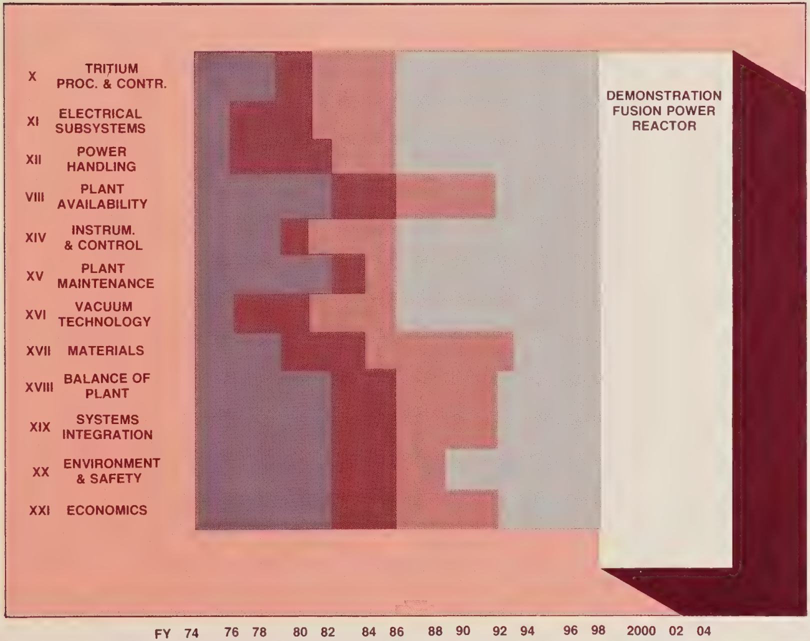


MAJOR PROGRAM ELEMENTS FLOW CHART
LOGIC III REFERENCE OPTION

Key

(1) Early Tests
(2) High Confidence Level Tests
(3) Definitive Tests
(4) Demo Prototype Tests

(1) Early Tests; (2) High Confidence Level Tests; (3) Definitive Tests; (4) Full Scale DEMO Prototype Tests. Gross program progress may be measured and described in the above terms for each fusion concept. Early tests provide the definition of the problems for the progress of each program element. High Confidence Level Tests are conducted via model and machine experiments. Definitive tests provide the full understanding of the scaling laws for the progress of a major element towards the DEMO reactor goal. Full scale DEMO prototype tests demonstrate the readiness for DEMO application.



CONCLUSIONS

Use of roll-back planning has

- highlighted the need to consider the desired end product: a commercial reactor, in laying out the R&D program.
- emphasized the relationship between schedule and the degree of risk associated with taking each new major step.

MAJOR PROGRAM ELEMENTS FLOW CHART LOGIC III REFERENCE OPTION

BUDGET REQUIREMENTS

LOGIC	$M I	II	III	IV	V
TOKAMAK FACILITIES		2630	2630	2630	4140
ENG. FACILITIES		875	875	1050	1710
ALT. CONC. FACILITIES		1600	2000	2000	4940
OPERATIONS		10120	9017	8260	8490
EQUIPMENT		1013	992	826	849
TOTAL		16238	15514	14766	20129

The total estimated funding required (in constant fiscal 1978 dollars) is shown at the left for each of the Logics. Budget detail is given for Logic III. The estimated costs are computed from FY 1978 through the date of operation of the DEMO. Logic III has been analyzed in detail. Logics II and IV were obtained as perturbations of Logic III. Logic V is a rough estimate and has not been carefully evaluated. Higher Logics have a higher degree of associated risk although they tend to cost less because of the smaller number of years required to reach the end goal.

PROGRAM COSTS BY YEAR FOR THE LOGIC III REFERENCE OPTION ($M)

ABBREVIATION KEY:

TFTR—TOKAMAK FUSION TEST REACTOR
PEPR/ITR—PROTOTYPE EXPERIMENTAL POWER REACTOR/IGNITION TEST REACTOR
EPR—EXPERIMENTAL POWER REACTOR
DEMO —DEMONSTRATION REACTOR
FERF/ETR—FUSION ENGINEERING RESEARCH FACILITY/ENGINEERING TEST REACTOR
HFNS—HIGH FLUX NEUTRON SOURCE
HTTF—HEATING TECHNOLOGY TEST FACILITIES
TF—TRITIUM FACILITY
B&S—BLANKET AND SHIELD FACILITY
RTNS—ROTATING TARGET NEUTRON SOURCE
INS—INTENSE NEUTRON SOURCE
PMCTF—PLASMA MAINTENANCE & CONTROL TEST FACILITIES
VTF—VACUUM TECHNOLOGY FACILITY
SMTF—SUPERCONDUCTING MAGNET TEST FACILITY
ETF—ENGINEERING TEST FACILITIES
ALTERNATE CONCEPTS
LARGE HYDROGEN EXPERIMENTS
LARGE STAGED SCYLLAC
LHX #3
LHX #4
MIRROR PEPR
ALTERNATE CONCEPTS PEPR
EXPERIMENTAL POWER REACTOR

	FY76	FY77	FY78
TOKAMAK FACILITIES	20	80	95
TFTR	20	80	95
PEPR/ITR Facility	0	0	0
PEPR/ITR Device	0	0	0
EPR	0	0	0
DEMO	0	0	0
ENGINEERING FACILITIES	2	18	20
FERF/ETR	0	0	0
HFNS	0	0	10
HTTF	0	0	0
TF	0	0	0
B&S	0	0	0
RTNS	2	3	0
INS	0	15	10
PMCTF	0	0	0
VTF	0	0	0
SMTF	0	0	0
Eng. Test. Fac.	0	0	0
ALTERNATIVE CONCEPTS FACILITIES	0	0	15
MX	0	0	15
LHX LSS	0	0	0
LHX #3	0	0	0
LHX #4	0	0	0
M-PEPR 1	0	0	0
A-PEPR 2	0	0	0
EPR	0	0	0
TOTAL FACILITIES	22	98	130
OPERATIONS	120	183	248
EQUIPMENT	17	23	32
TOTAL PROGRAM	159	304	410

'79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88	FY89	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	21 yr. Total FY78-98
50	65	115	140	105	45	15	40	120	240	240	120	40	60	120	240	360	240	120	60	2630
35	15	35	35	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	230
15	35	35	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
0	15	45	90	90	45	15	0	0	0	0	0	0	0	0	0	0	0	0	0	300
0	0	0	0	0	0	0	40	120	240	240	120	40	0	0	0	0	0	0	0	800
0	0	0	0	0	0	0	0	0	0	0	0	0	60	120	240	360	240	120	60	1200
20	45	82	79	60	100	160	172	102	35	0	0	0	0	0	0	0	0	0	0	875
0	0	0	0	25	75	150	150	75	25	0	0	0	0	0	0	0	0	0	0	500
15	20	20	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75
0	0	6	9	0	0	0	6	9	0	0	0	0	0	0	0	0	0	0	0	30
5	10	20	10	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
0	5	10	20	10	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
0	0	3	5	0	0	0	3	4	0	0	0	0	0	0	0	0	0	0	0	15
0	0	3	5	0	0	0	3	4	0	0	0	0	0	0	0	0	0	0	0	15
0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
0	10	20	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	0	0	100
35	35	60	105	105	65	60	120	140	120	140	120	100	140	240	240	120	40	0	0	2000
35	35	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
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0	0	15	35	35	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
0	0	0	0	0	20	60	120	120	60	20	0	0	0	0	0	0	0	0	0	400
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0	0	0	0	0	0	0	0	0	0	0	0	40	120	240	240	120	40	0	0	800
05	145	257	324	270	210	235	332	362	395	380	240	140	200	360	480	480	280	120	60	5505
80	327	346	376	390	400	410	420	430	440	450	460	470	480	490	500	510	520	530	540	9017
45	55	45	55	55	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	992
30	527	648	755	715	648	686	794	835	879	875	746	657	728	899	1030	1041	852	703	654	15514

DETAIL

Details of the Fusion Power Program are given in a set of four volumes.

Volume I: Summary, ERDA-76/110/1

Volume II: Long Range Planning Projections, ERDA-76/110/2

Volume III: Five Year Plan, ERDA-76/110/3

Volume IV: Five Year Budget and Milestone Summaries, ERDA-76/110/4

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